Microlensing

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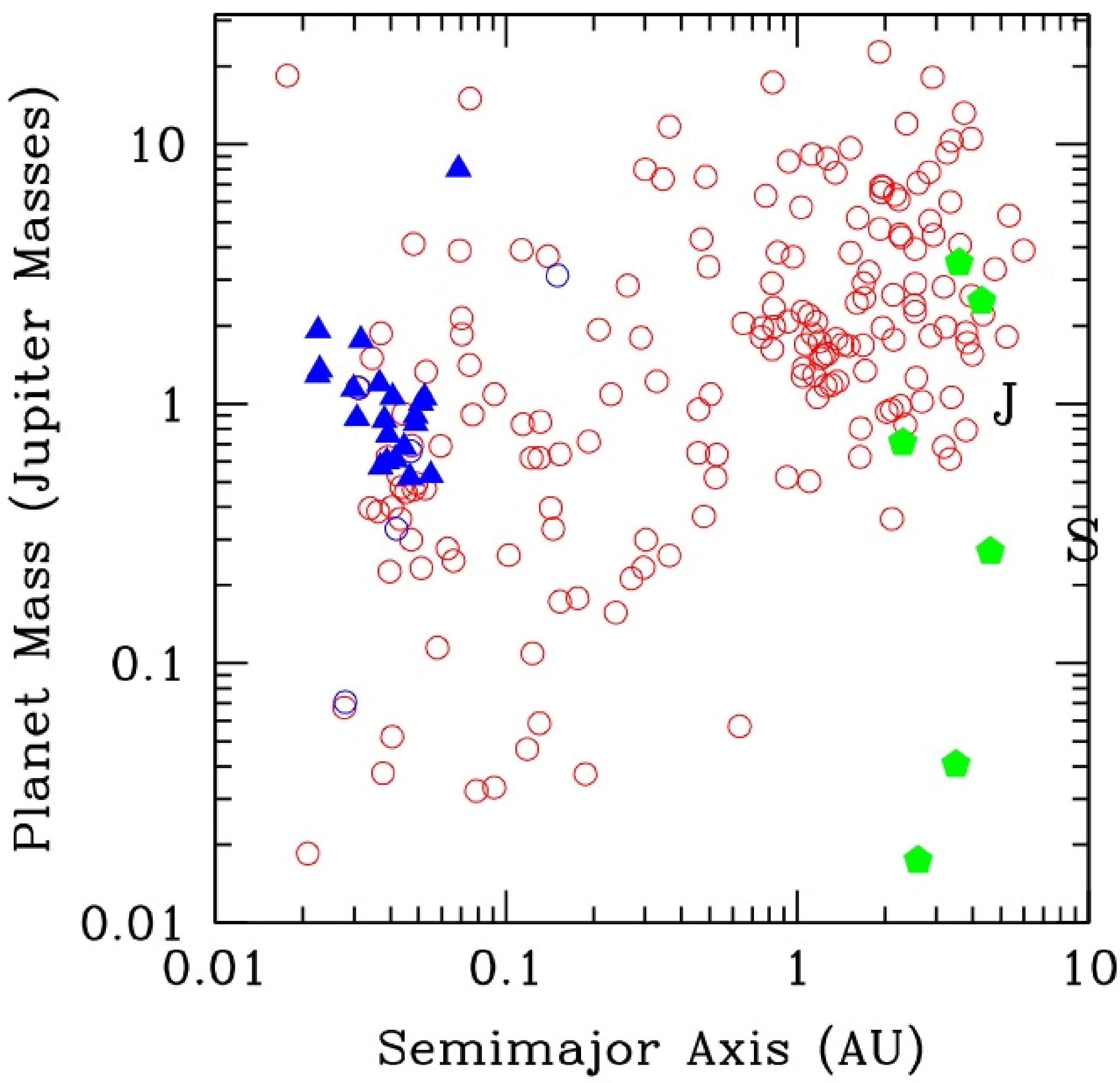
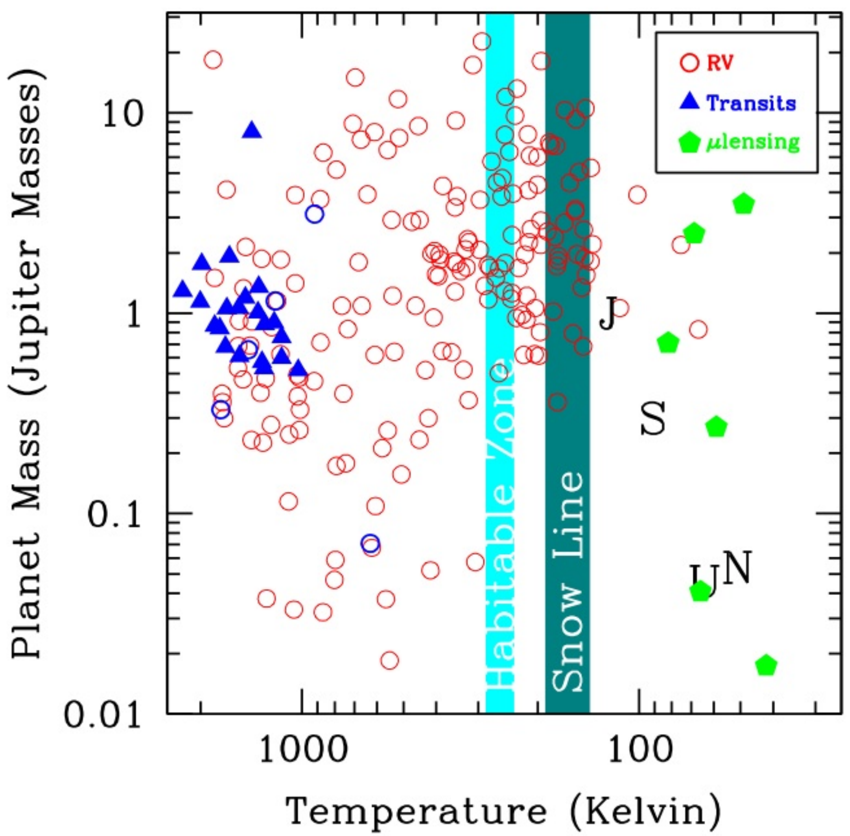
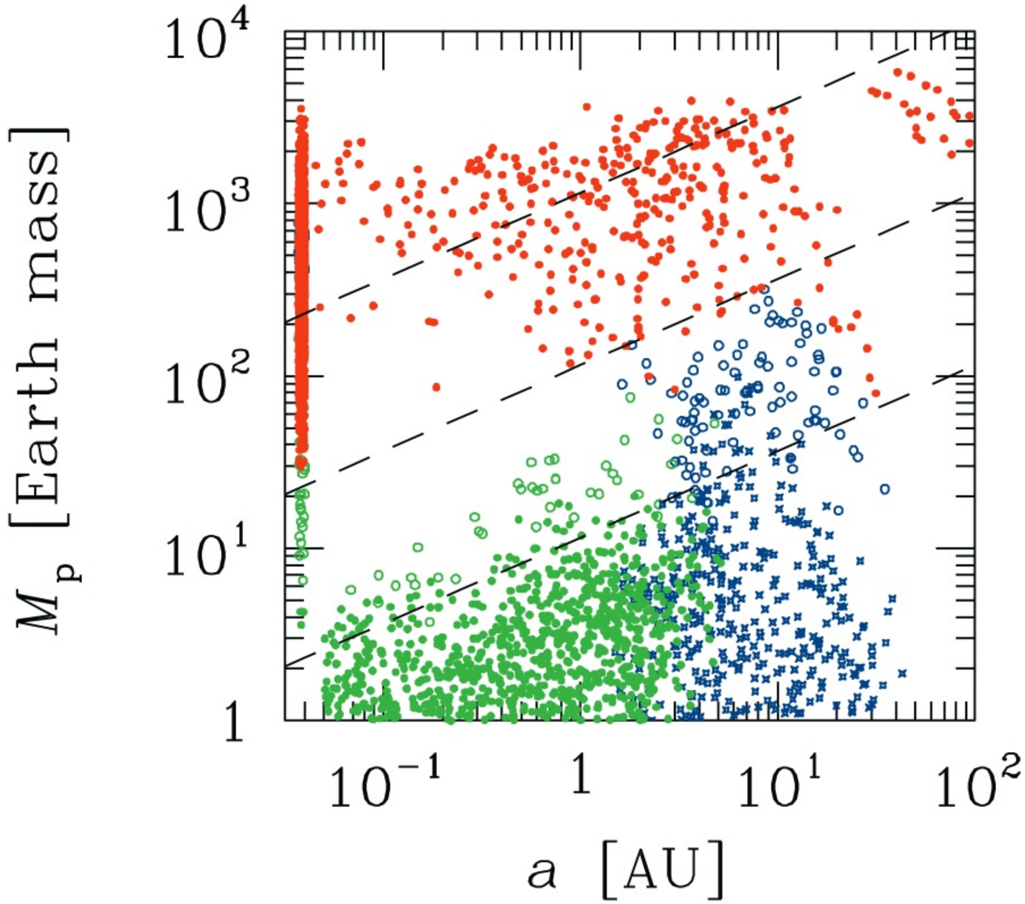
Microlensing Peculiarities

- Microlensing planet community is comparatively small.
- General consensus on forward directions.
- Two (and only two) paths forward
  - Ground based, 1-5 years, ~$10-20M
    - Frequency of planets $>M_{\oplus}$ beyond the snow line.
  - Space based, 5-10 years, ~$300M
    - Complete census of planets with mass greater than Mars and $a > 0.5$ AU, including habitable planets.



Planet Mass (Jupiter Masses)
10
1
0.1
0.01
0.01
0.1
1
10
Semimajor Axis (AU)
J
S

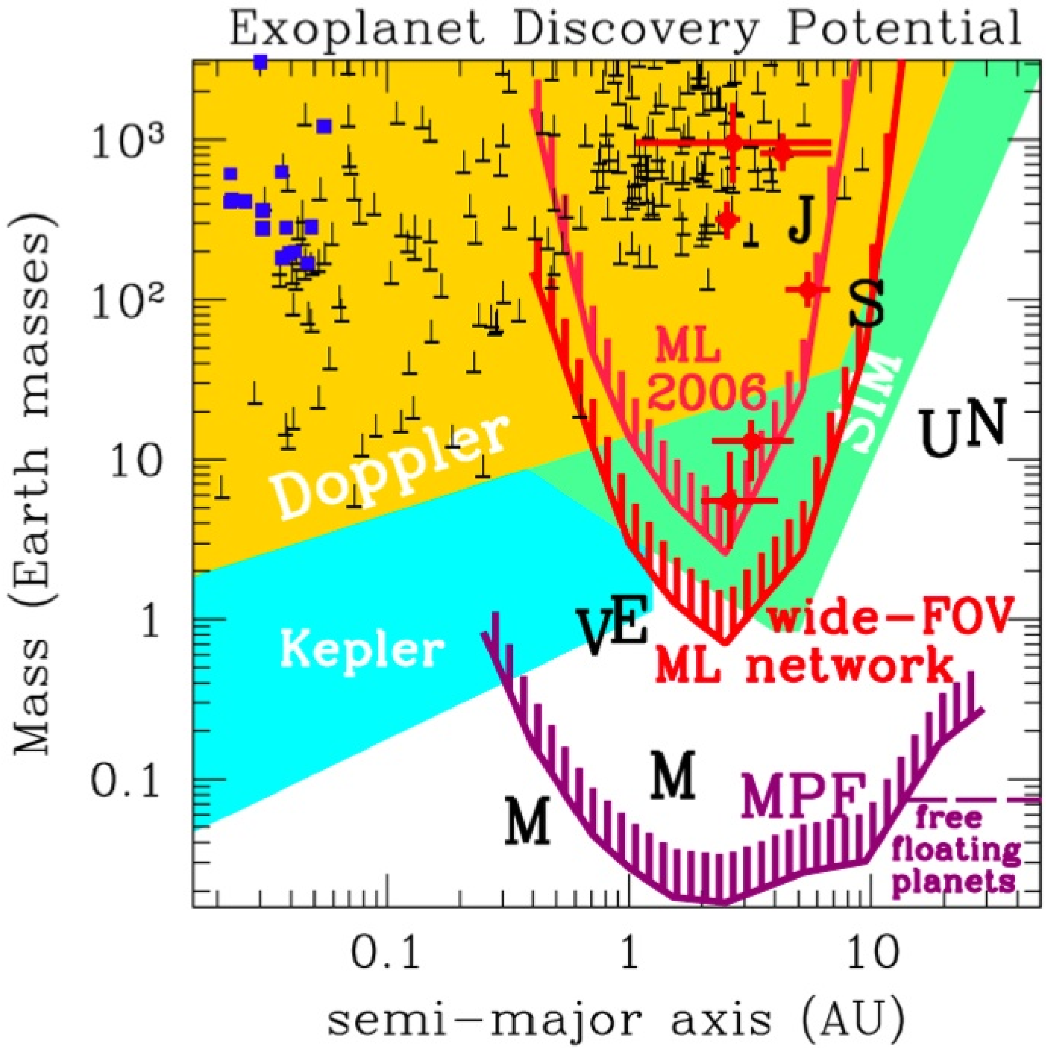




Beyond the snow line:

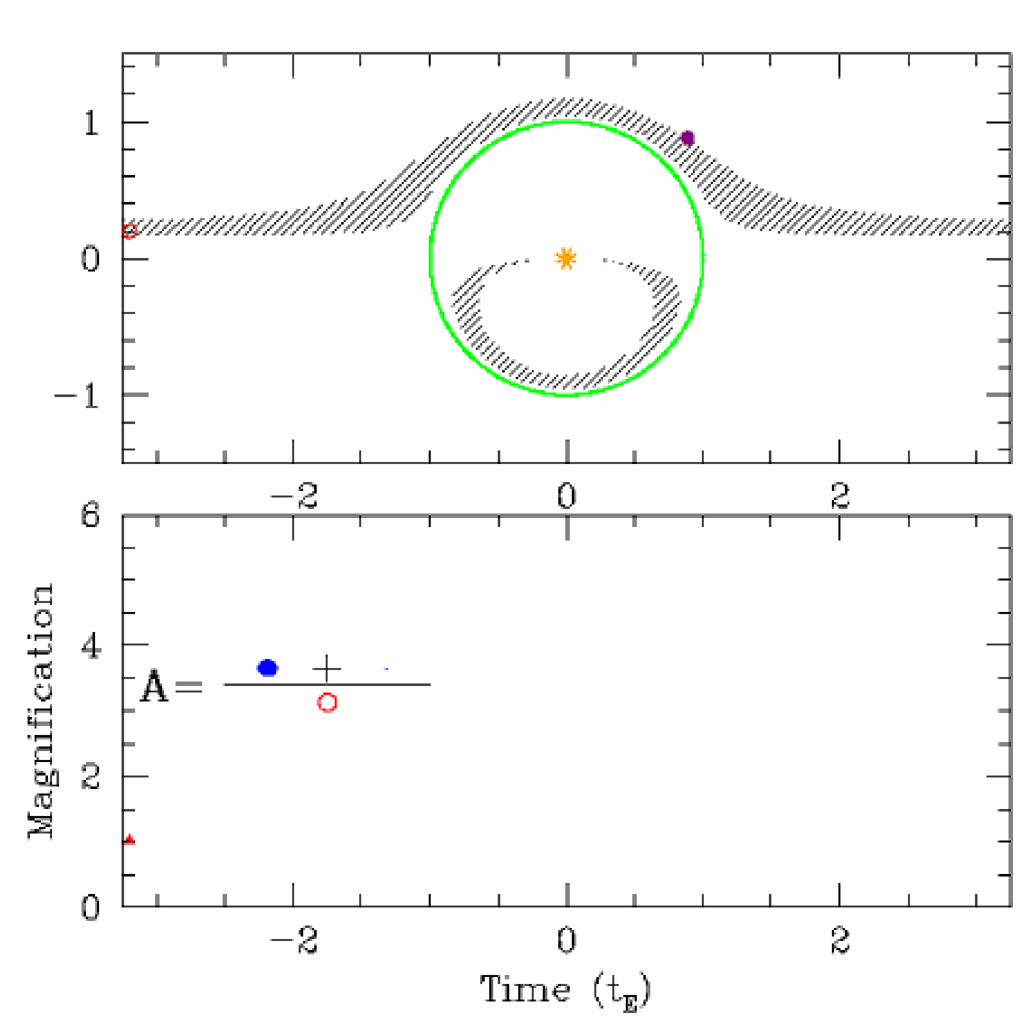
- Location of giant planet formation (and our giant planets).
- ‘Failed Jupiters’
- Source of water

Ground-based μlensing surveys probe planets with $M>M_\oplus$ beyond the snow-line.



A space-based survey will provide a complete census of planetary systems with mass greater than Mars and a>0.5 AU (from 0 to ∞ with Kepler), including habitable planets.

Detecting Planets



Primary event:

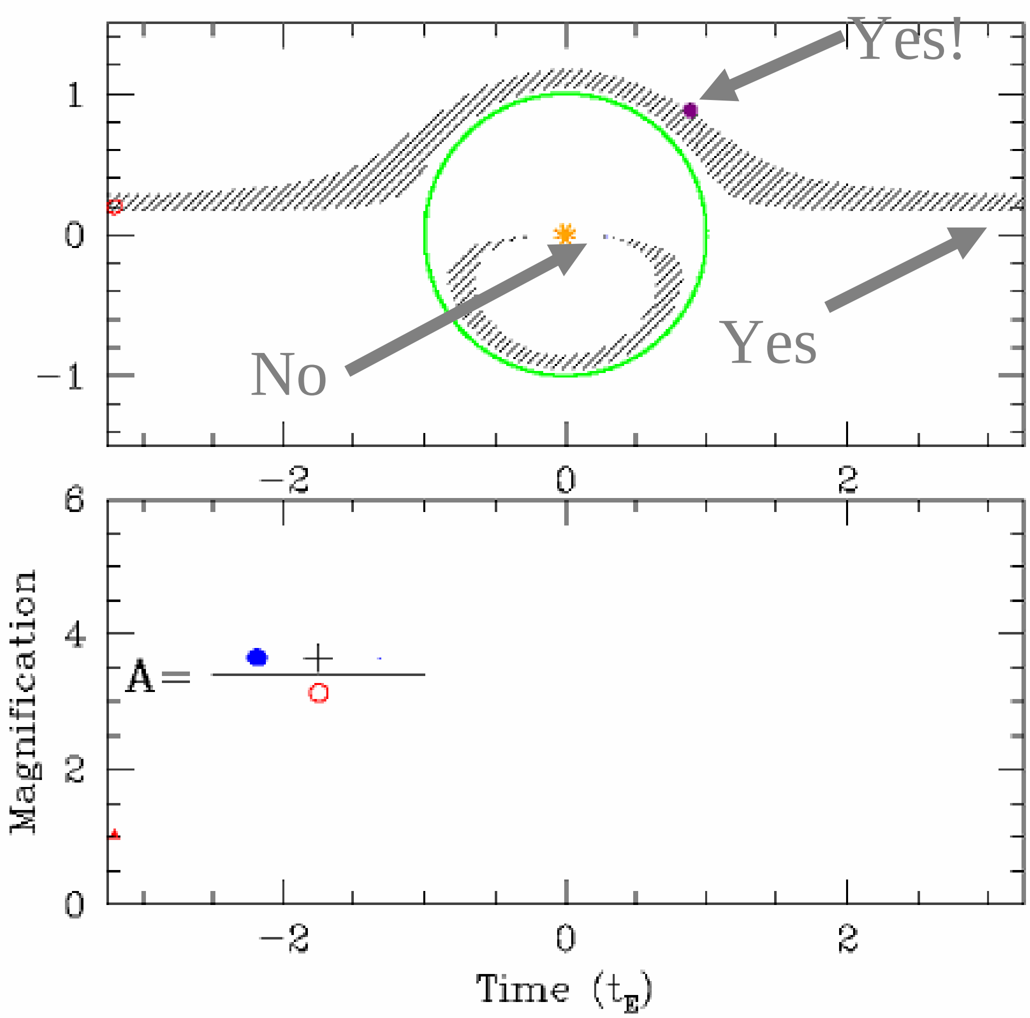
- Smooth, symmetric
- Typically 20 days

Planetary perturbation to images

- Short-timescale bump
- Measure:
  - Projected Separation
  - Mass Ratio

$$t_p = q^{1/2} t_E \approx 1 \text{ day} \left(\frac{M_p}{M_J} \right)^{1/2}$$

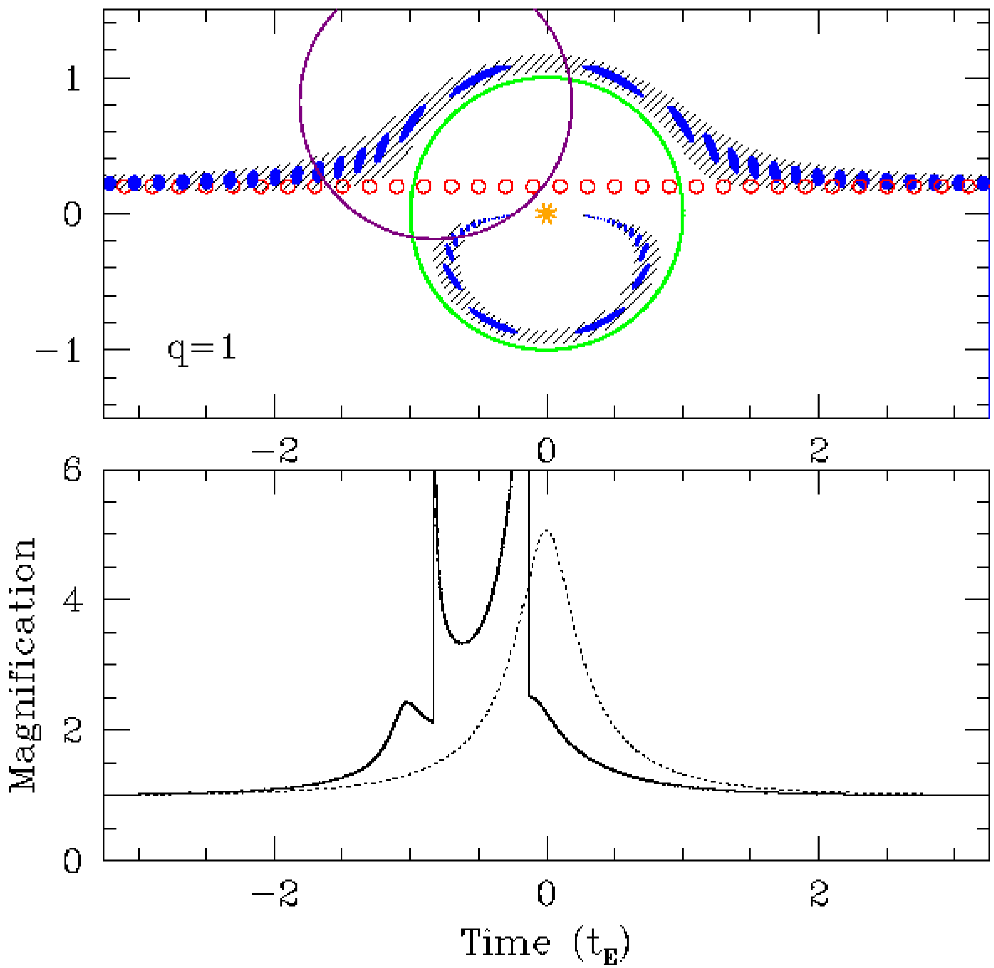
Microlensing is directly sensitive to planet mass



- Works by perturbing images
- Does not require light from the lens or planet.
- Sensitive to planets in the disk and bulge with D_{OL}=1-8 kpc
- Most sensitive to planets near the Einstein radius
- Sensitive to wide or free-floating planets
- Not sensitive to very close planets

Very Low Mass Planets

Signal magnitude is *independent* of planet mass.

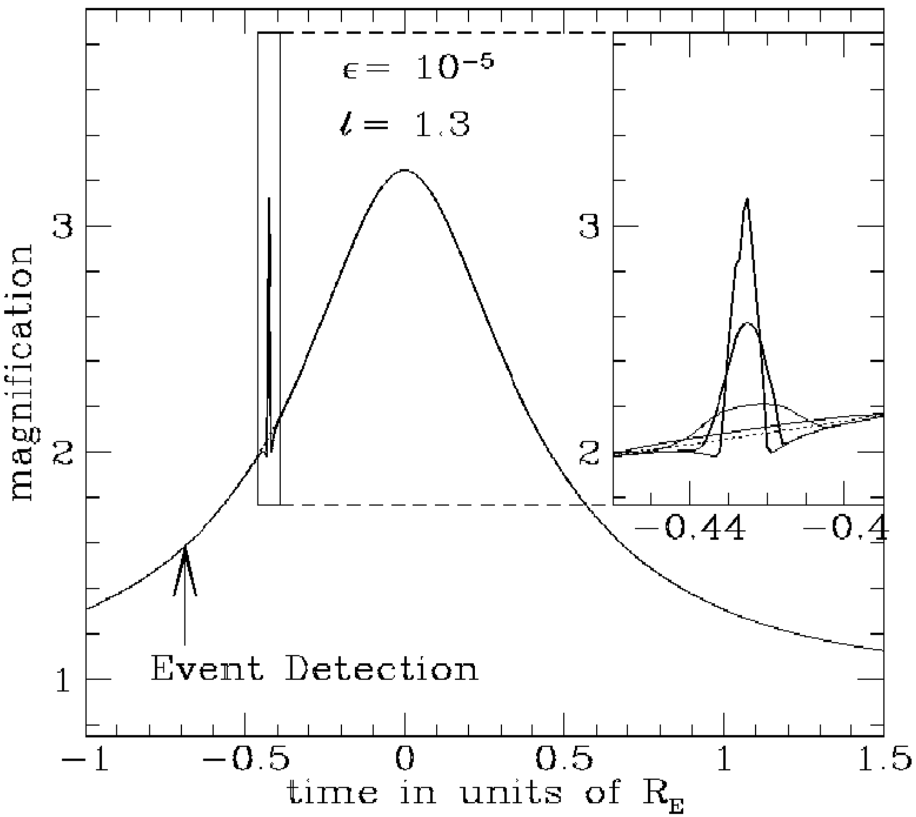


- Magnitude depends on separation of planet from image.
- Duration depends on mass.

$$\boxed{t_p = q^{1/2} t_E \approx 2\ \text{hrs} \left(\frac{M_p}{M_{\circ Ú}}\right)^{1/2}}$$

- Signals get rarer and briefer.
- Detection Probability
  ~ few %
- Large (~10%) signals for low-mass (Earth-mass) planets

How Low Can We Go?



(Bennett & Rhie 1996)

- Limited by Source Size

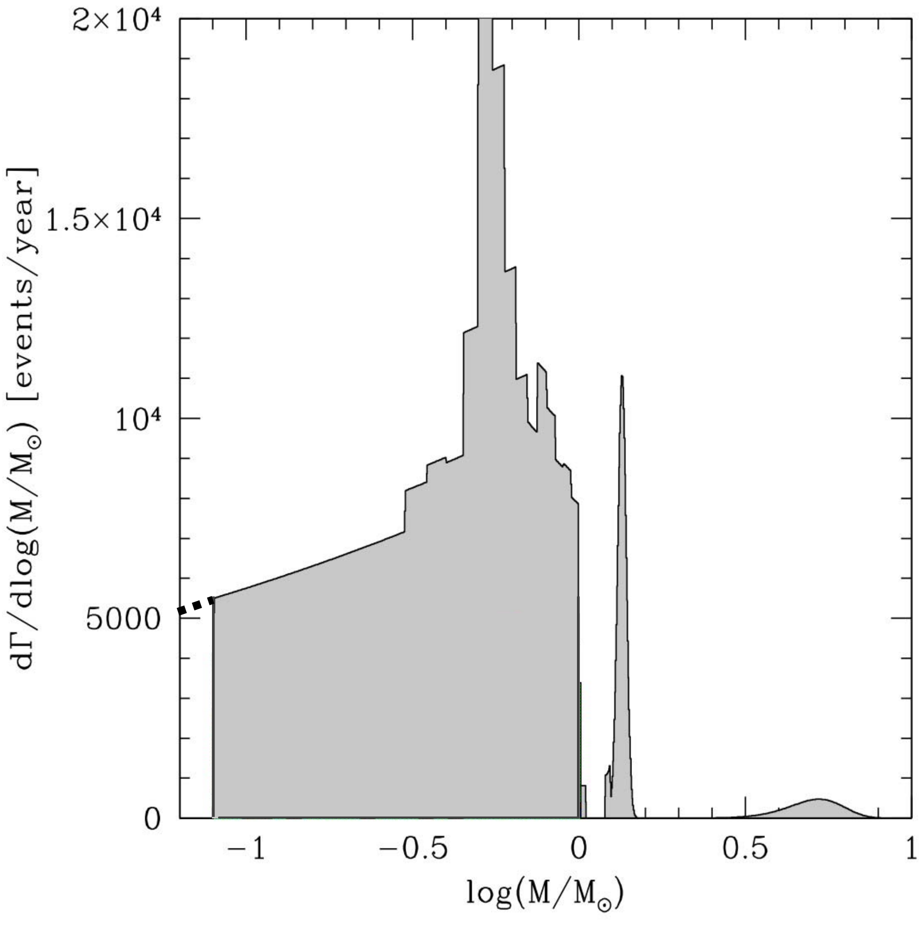
$$\boxed{\rho_* = \frac{\theta_*}{\theta_E} \approx 1}$$

$$\boxed{\theta_E \approx \mu\text{as}\left(\frac{M_p}{M_\odot}\right)^{1/2}} \Longleftrightarrow \boxed{\theta_* \approx \mu\text{as}\left(\frac{R_*}{R_\odot}\right)}$$

Mars-mass planets detectable

if solar-type sources can be monitored!

Sensitivity Depends Weakly on Host Mass



Sensitive to planets around:

- Main-sequence stars with $M < M_\odot$
- Brown dwarfs
- Remnants

Microlensing Strengths

- Peak sensitivity beyond the snow line.
  - 50-100K
- Sensitivity down to ***very*** low-mass planets.
  - Mass greater than that of ~10% Mars.
- Sensitivity to long-period and free-floating planets.
  - 0.5 AU - ∞
- Sensitivity to planets over a wide range of host masses.
  - $M < M_{\odot}$
- Sensitivity to planets throughout the Galaxy.
  - 1-8 kpc
- Sensitivity to multiple-planet systems.

Commonly heard complaints…

- But you don't know anything about the star, orbits, etc!

— Typically can measure host star and planet masses to ~10-20%.

— In some special cases can learn something about the orbit.

- But the systems are so far away and faint!

— Sufficiently bright to measure flux, color, and in some cases get spectra.

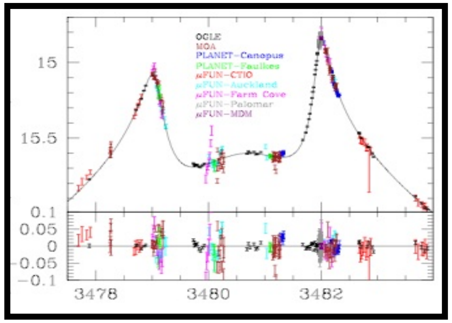
- But you only see it once!

— Signals are large and unambiguous.

— Demographics of planetary systems.

First Four Detections

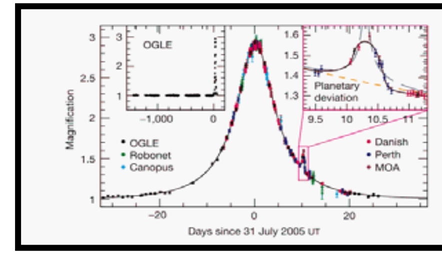
OGLE-2005-BLG-071
(Udalski et al 2005)



$M_p \sim 3.5 M_J, \;\; r \sim 3.6\,\mathrm{AU}$

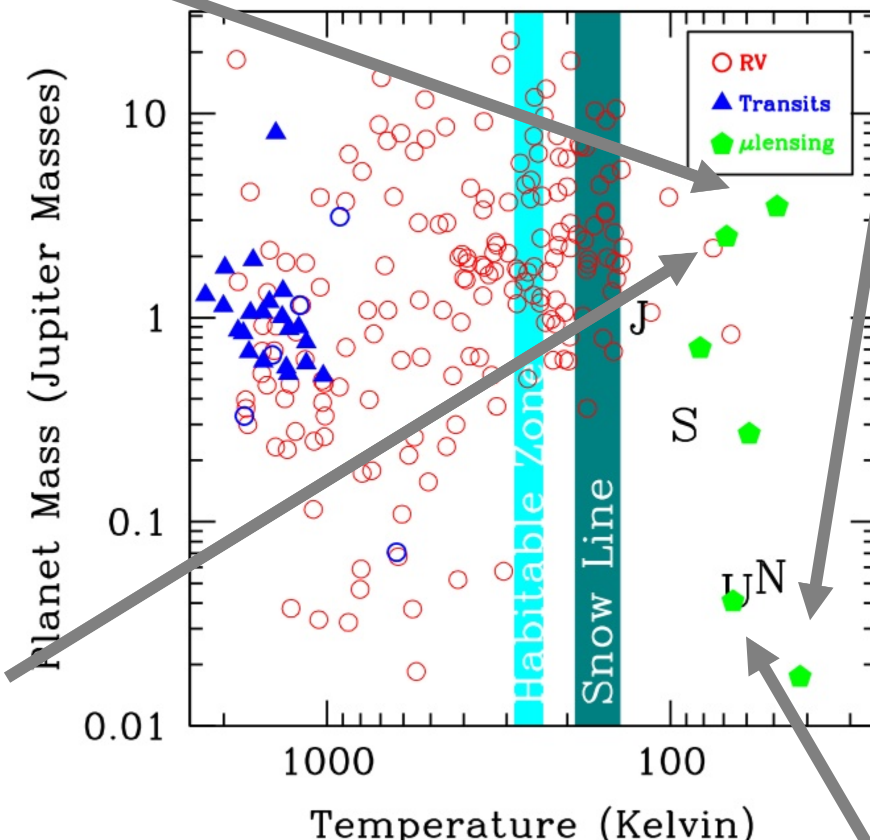
$M_* \sim 0.46 M_\odot, \;\; D_{OL} \sim 3.3$ kpc

OGLE-2005-BLG-390
(Beaulieu et al 2006)

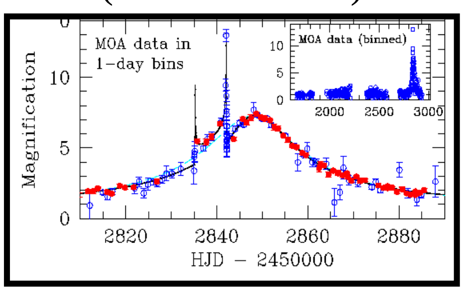


$M_p \sim 5.5 M_\oplus, \;\; r \sim 2.6\,\mathrm{AU}$

$M_* \sim 0.22 M_\odot, \;\; D_{OL} \sim 6.6$ kpc



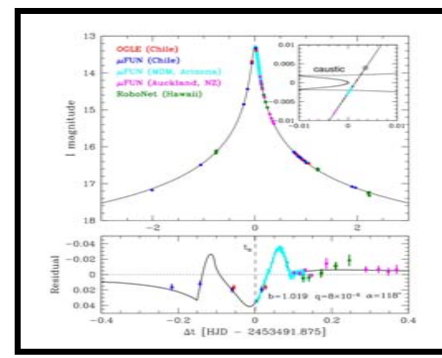
OGLE-2004-BLG-235
MOA-2004-BLG-53
(Bond et al 2004)



$M_p \approx 2.5 M_J, \;\; r \approx 4.3\,\mathrm{AU}$

$M_* \sim 0.63 M_\odot, \;\; D_{OL} \sim 5.2$ kpc

OGLE-2005-BLG-169
(Gould et al 2006)



$M_p \sim 13 M_\oplus, \;\; r \sim 3.5\,\mathrm{AU}$

$M_* = 0.5 M_\odot, \;\; D_{OL} = 2.7$kpc

Two Jovian-mass planets
Two Neptune-mass planets

Cool Neptunes Are Common

Two low-mass detections imply:

~37% of stars have Neptunes between 1.6-4.3 AU (16-69% at 90% confidence)

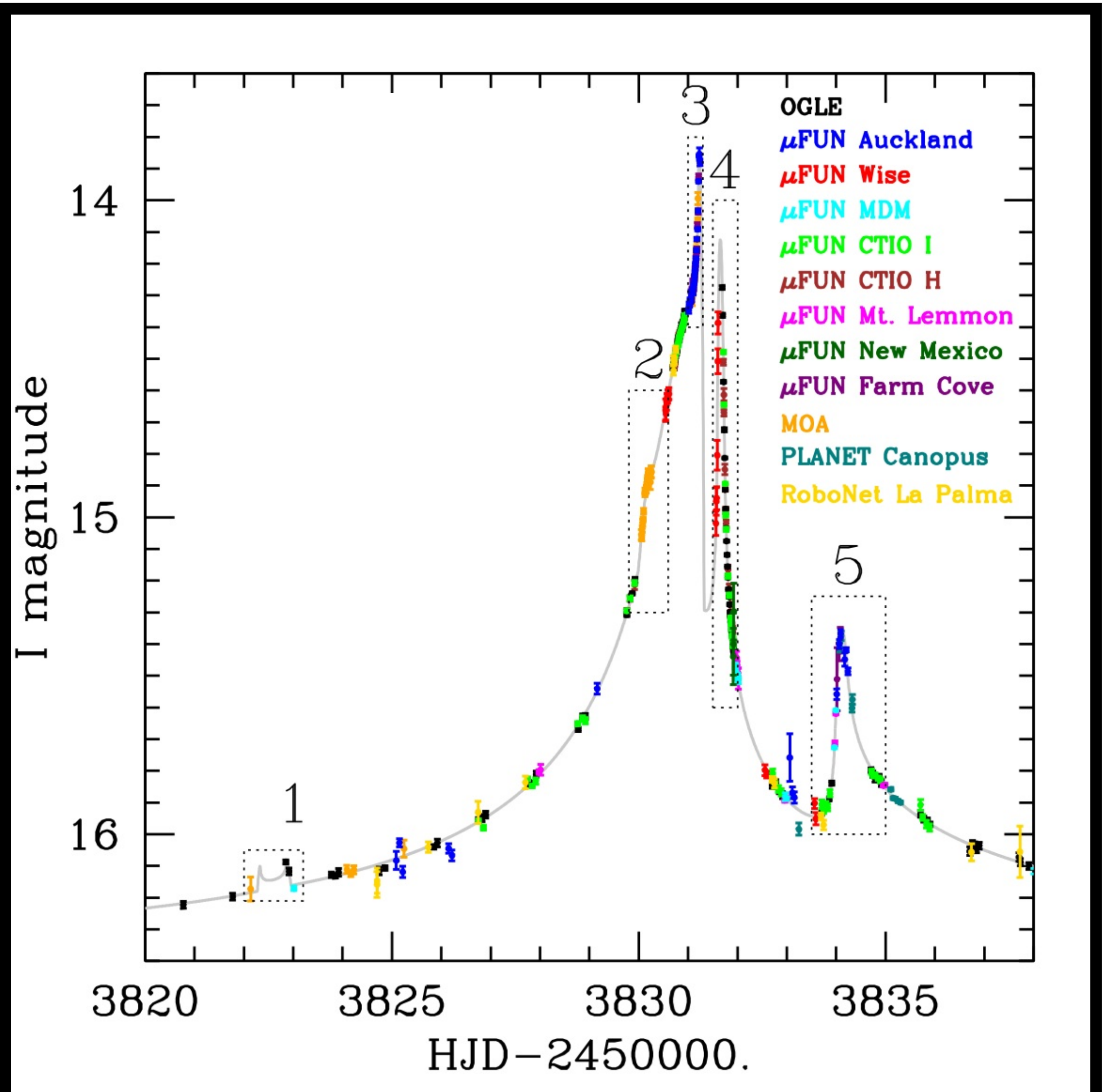
dN/dloga ~ 1 at **~3 AU** (0.4-1.6 at 90%)
dN/dloga ~ 0.3 at **~0.15 AU** (HARPS)

Also:

Cool Neptunes are more common than cool Jupiters

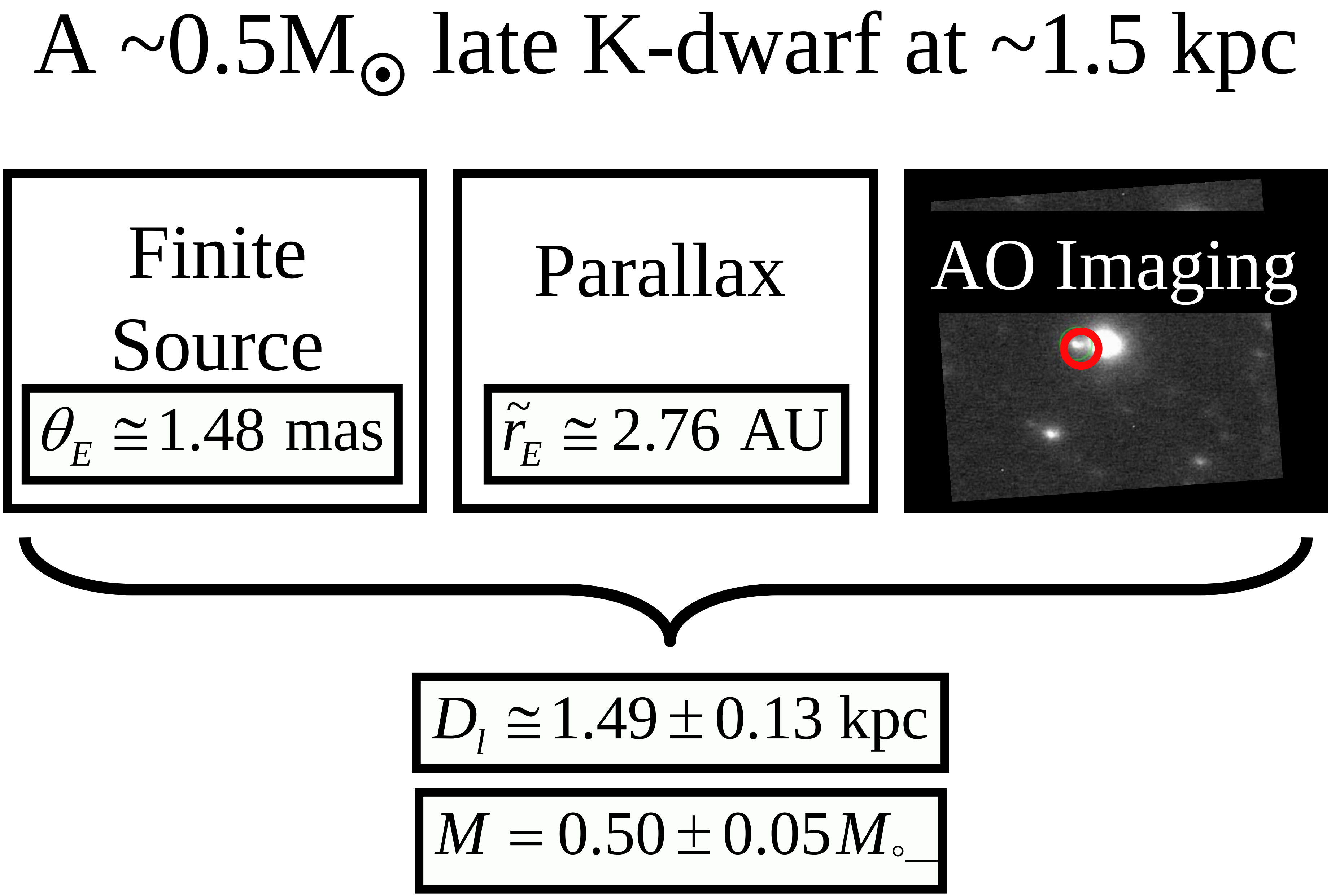
Multiple System

(Gaudi, Bennett et al 2008)



- High-magnification Event
  - μFUN, OGLE, MOA
- Must include two planets, finite source, orbital motion, and parallax
- Yields full star and planet masses, information on orbital speed of Saturn and inclination!

High-magnification Event, monitored by μFUN, OGLE, MOA



A ~0.5M$_\odot$ late K-dwarf at ~1.5 kpc
Finite Source
$\theta_E \simeq 1.48$ mas
Parallax
$\tilde{r}_E \simeq 2.76$ AU
AO Imaging
$D_l \simeq 1.49 \pm 0.13$ kpc
$M = 0.50 \pm 0.05 M_\odot$

The OGLE-2006-BLG-109L Planetary System

Planet b:

Mass = $0.71 \pm 0.08\ M_{Jup}$

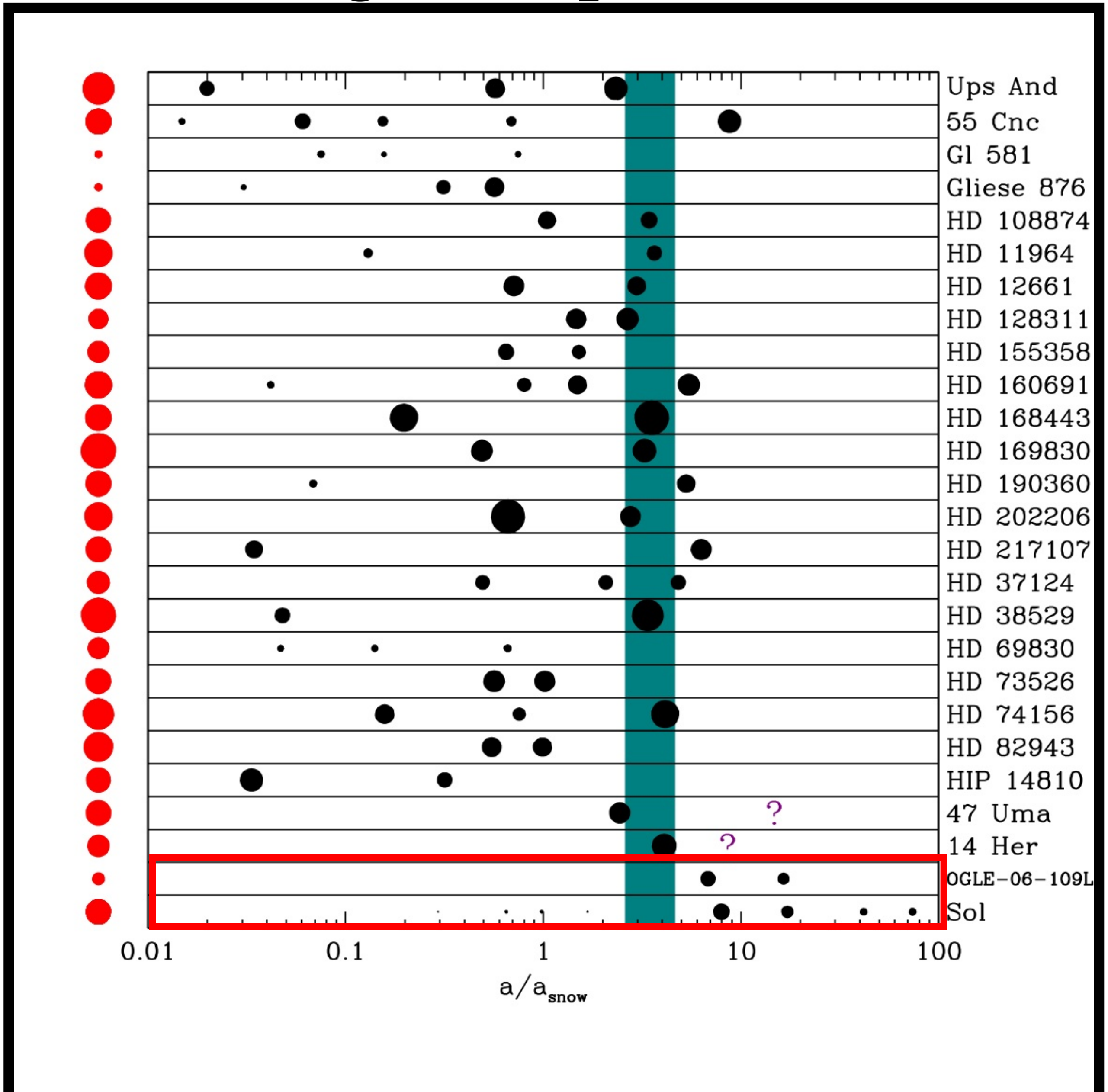
Semimajor Axis = 2.3 ± 0.2 AU

Planet c:

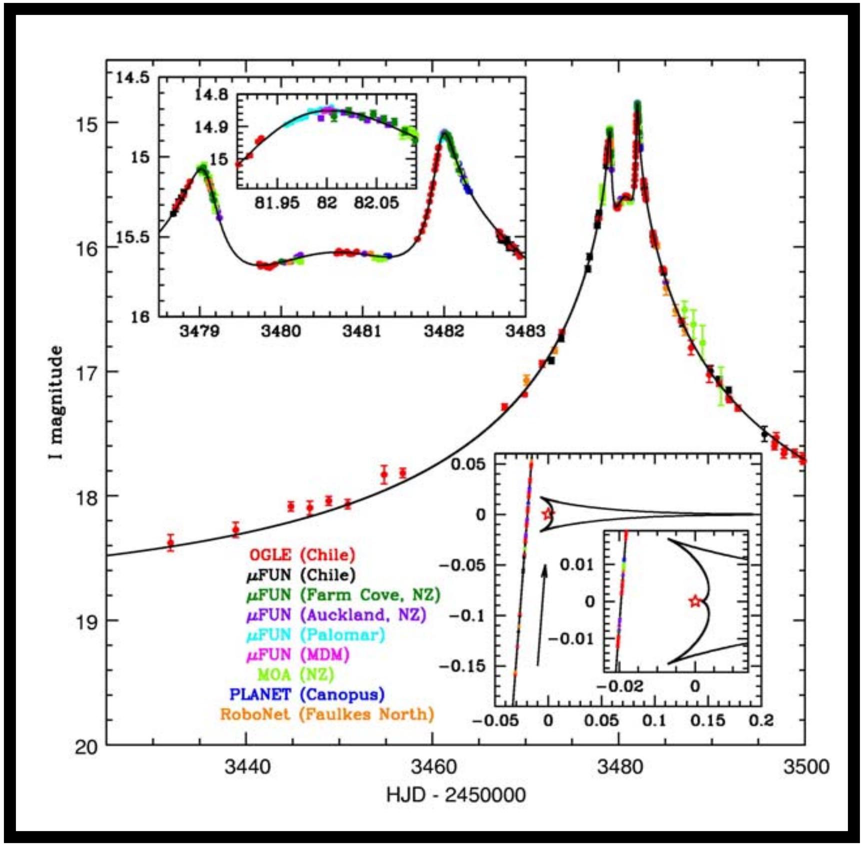
Mass = $0.27 \pm 0.03\ M_{Jup} = 0.90\ M_{Sat}$

Semimajor Axis = 4.6 ± 0.5 AU

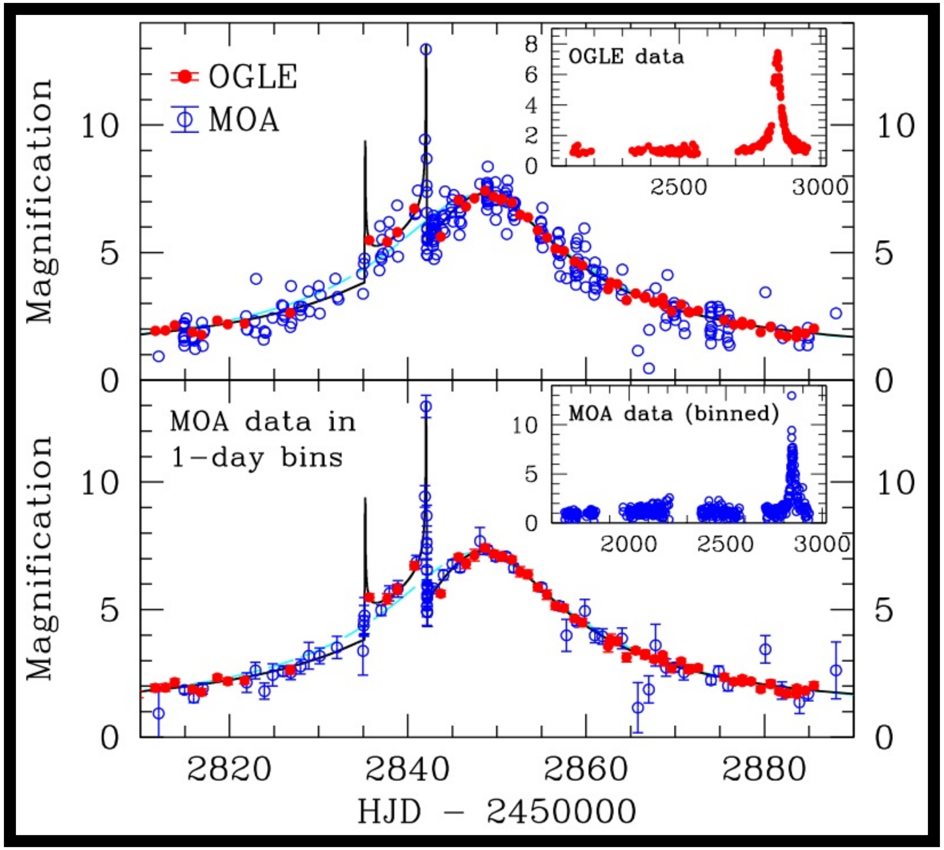
Analog of Jupiter/Saturn



Implications for Frequency of Systems



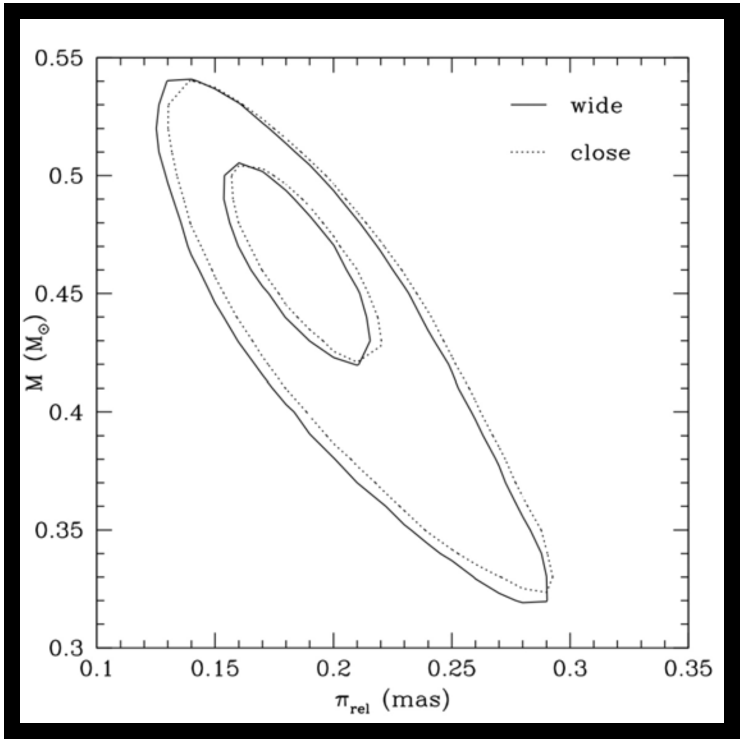
(Udalski et al. 2005)



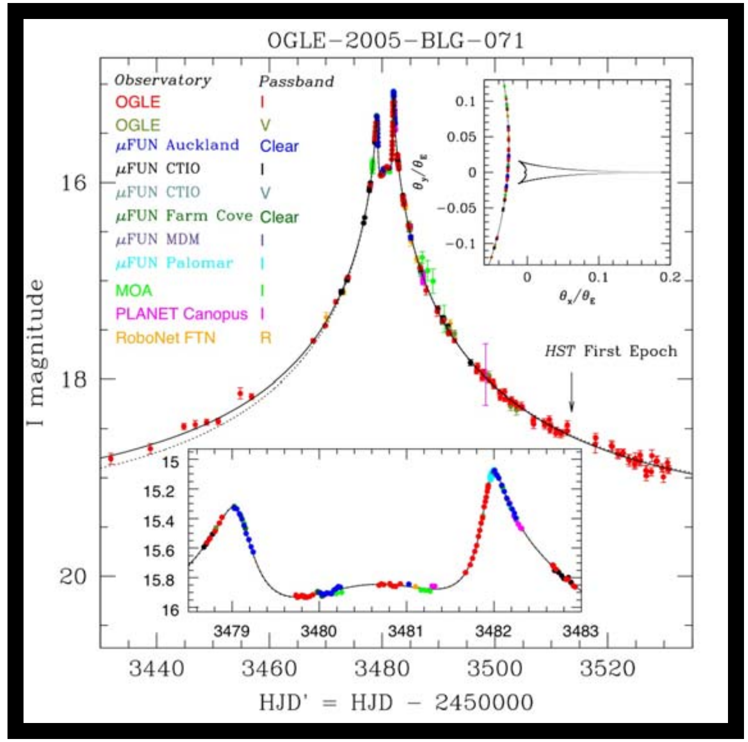
(Bond et al. 2004)

The Most Massive M Dwarf Planet?

(Dong et al 2008)



Dong et al. 2008



$$M = 0.46 \pm 0.04 M_{\circ}$$

$$D_l = 3.3 \pm 0.4 \text{ kpc}$$

$$v_{\mathrm{LSR}} = 103 \pm 14 \text{ km s}^{-1}$$

$$m = 3.5 \pm 0.3 M_{\mathrm{Jup}}$$

$$r_{\perp} = 3.6 \pm 0.2 \text{ AU}$$

$$T_{eq} \sim 50K$$

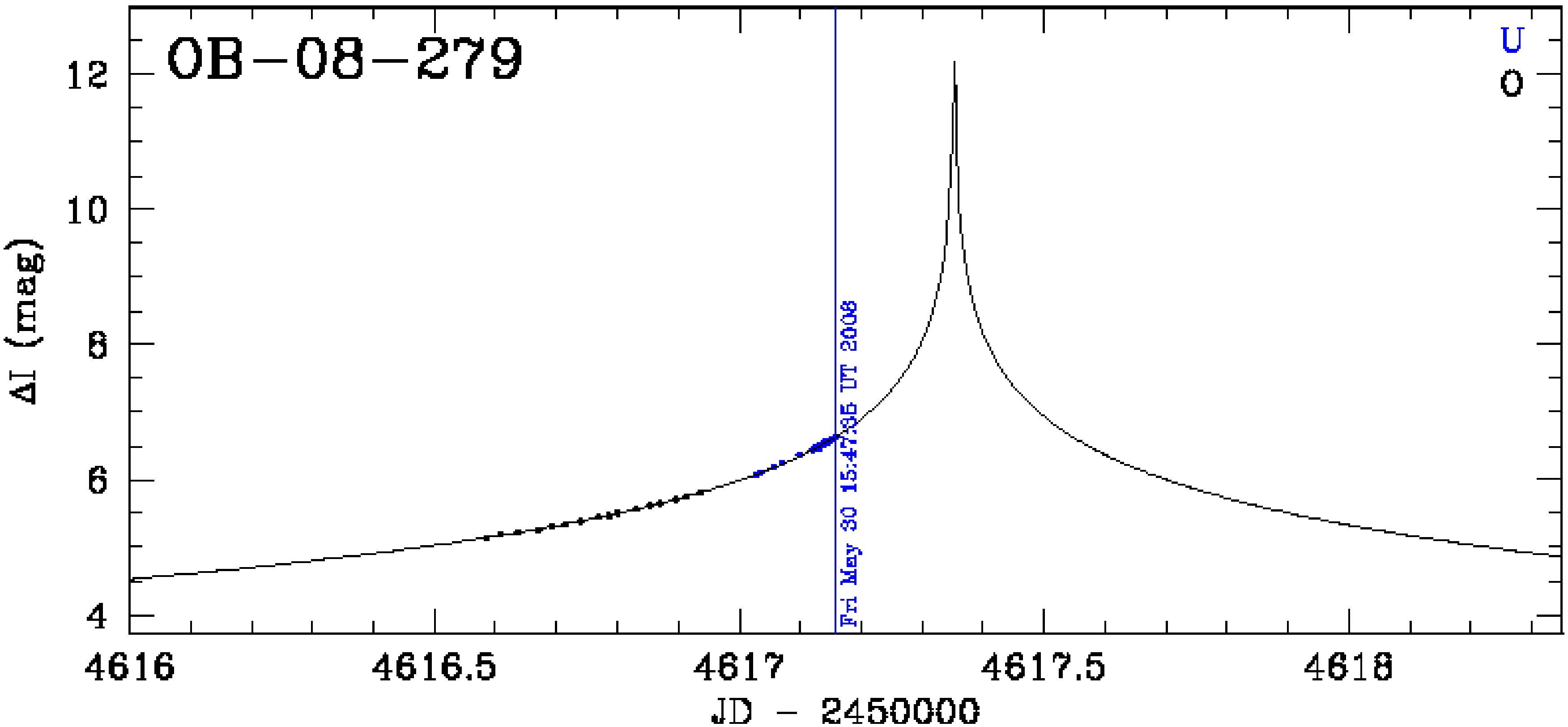
More on the way…

- **Five or six additional planets in 2007.**
  - Lowest mass planet around lowest mass host (Bennett et al, submitted).
  - Jupiter-mass planet.
  - Another multiple planet system.

- **2008 season underway.**
  - Jupiter-mass planet found two weeks ago.

- **Can expect ~half a dozen planets per year.**

Current High-Magnification Event



Peak at ~UT 20:30 (~1:30 PDT), magnification >1400
Sensitive to Earth-mass planets near the Einstein ring.

What’s Next?

- **Current setup (alert/follow-up) saturated**
  - Nearly all of the useable bulge monitored
  - Many events cannot be monitored
  - Monitoring one event at a time too inefficient
- **A new strategy**
  - Dispense with alert/follow-up
  - Simultaneously detect and monitor microlensing events

What is Required?

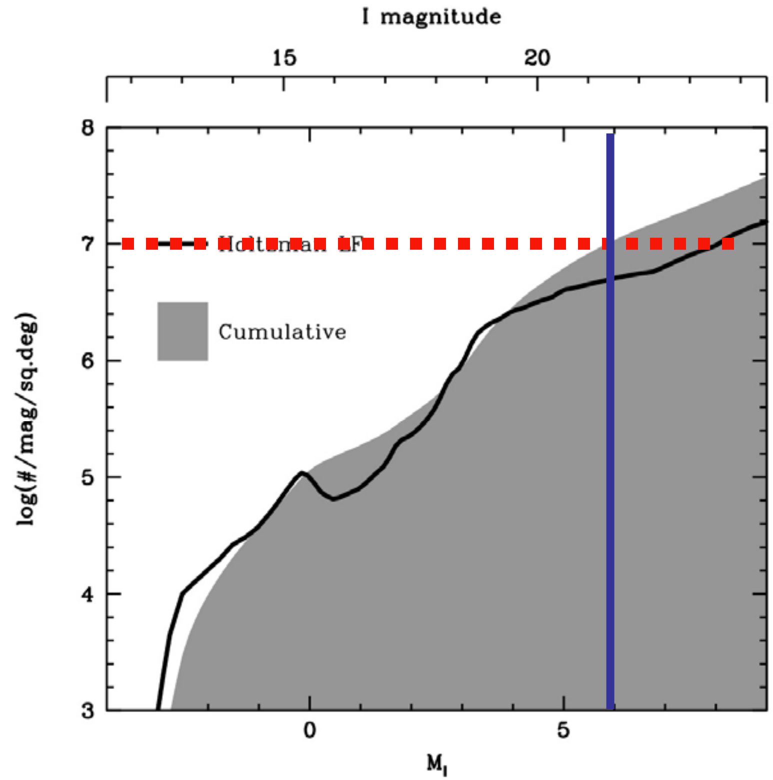
- Event Rate
  - Primary Event Rate

$$L \approx 10_{-5}\,\lambda\mathrm{L}_{-1}$$

  - Detection Probability

$$\mathrm{P} \approx \forall_0 \theta_p \approx 1\% \left(\frac{M_{\mathrm{Earth}}}{M_p} \right)_{1/2}$$

  - Detections Per Year



$$N \approx n_E \mho \Phi L \mathrm{P} \approx 10\ \lambda\mathrm{L}_{-1} \left(\frac{10^{\circ} \mathrm{Ð}}{\mho} \right) \left(\frac{10^{\prime}\ \mathrm{pÐ}}{\Phi} \right) \left(\frac{10_{-5}\ \lambda\mathrm{L}_{-1}}{L} \right) \left(\frac{1\%}{\mathrm{P}} \right)$$

What is Required?

Detecting the Perturbations from Earth-mass Planets

- Sampling rate ~ 10 minutes

$$\boxed{t_{E,p} = 2\,\mathrm{hrs}\left(\frac{M_p}{M_E}\right)^{1/2}}$$

- Photometric Accuracy ~ 1% at I~21
  - Signal Magnitude

$$\boxed{\frac{\Delta F}{F} \approx 1\%\left(\frac{M_p}{M_\odot}\right)\left(\frac{R_*}{R_\odot}\right)^{-2}}$$

  - Photometric Uncertainty

$$\boxed{\sigma = 1\%\left(\frac{D}{2\mathrm{m}}\right)^{-1}\left(\frac{t_{exp}}{120\mathrm{s}}\right)^{-1/2} 10^{0.2(I-21)}}$$

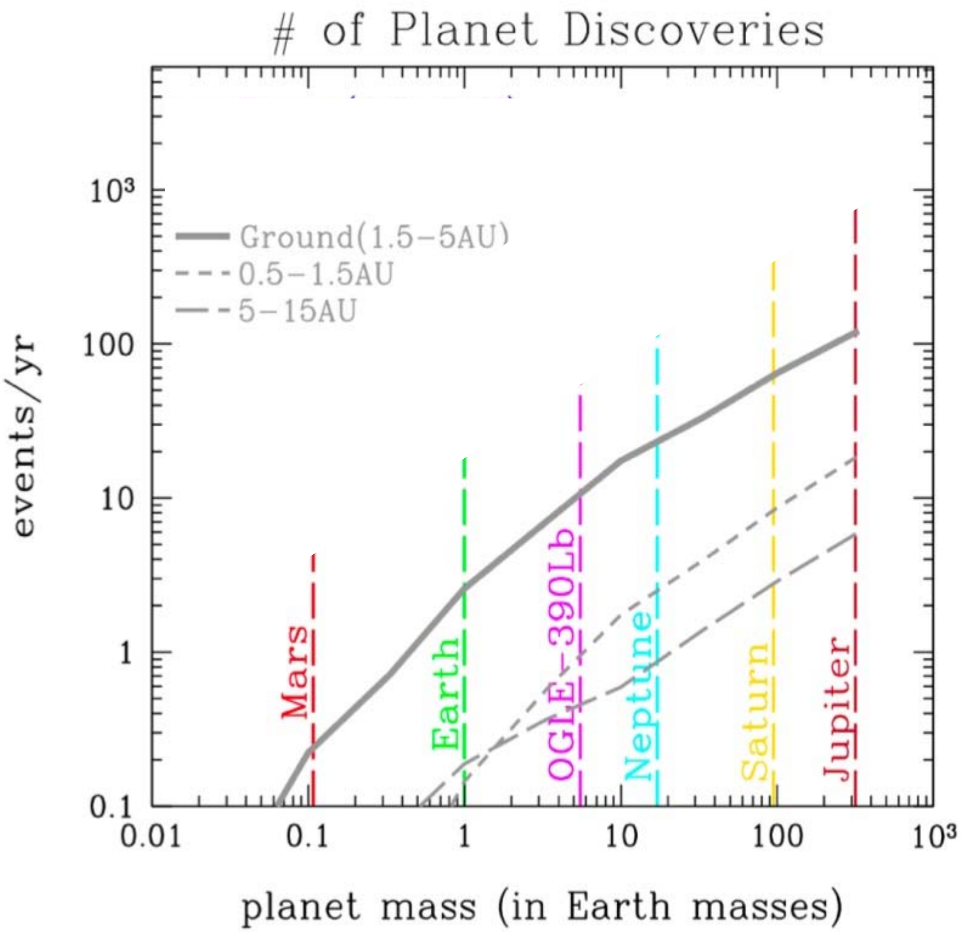
NextGen μLensing Survey

- Requirements to detect ~10 Earth-mass planets per year:

  – Monitor ~10 square degrees of the Galactic bulge continuously with ~10 minute sampling using 1-2m class telescopes, distributed longitudinally throughout the southern hemisphere.

  – Large FOV (2-4 square degree) cameras needed.

Expected Results



A next-generation ground-based μlensing survey can test planet formation by probing planets with $M > M_\oplus$ beyond the snow-line.

Spontaneous Generation

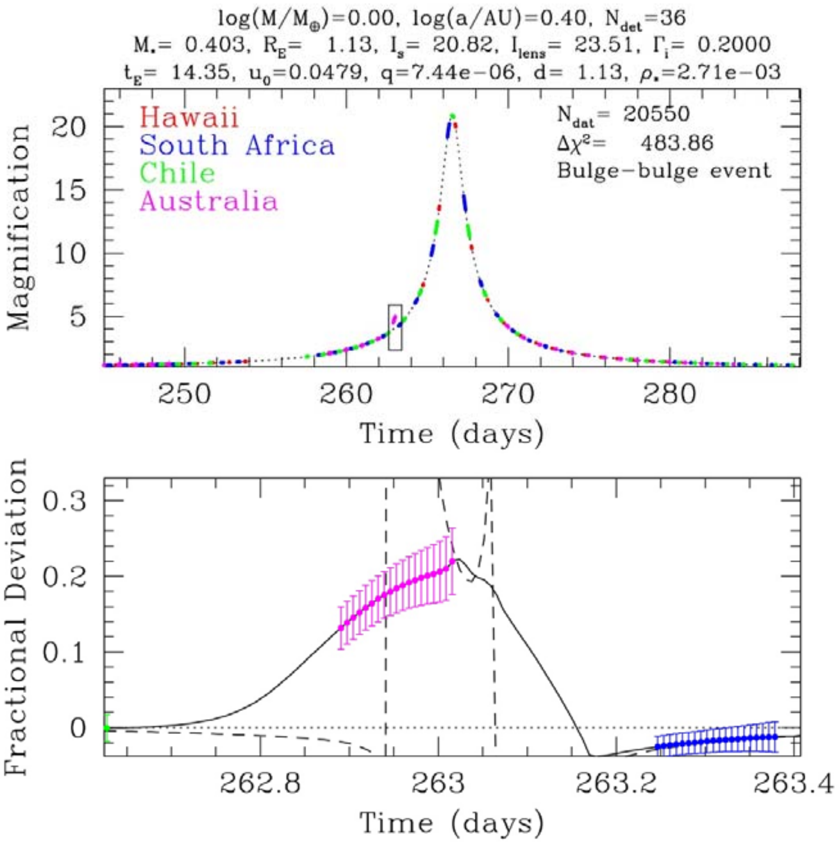
- MOA-II (NZ, currently operating)
  - 1.8m telescope, 2.18 sq. degree camera
- OGLE -IV (Chile, 2010)
  - 1.3m telescope, upgrade to 1.4 sq. degree camera
- All that is needed is a 1-2m telescope with a large FOV in South Africa.

“Recommendation A. II. 1 Increase dramatically the efficiency of a ground-based microlensing network by adding a single 2 meter telescope.”

Why Space is Better

From the ground:

- MS sources severely blended
- Getting constraints on hosts is expensive
- Perturbations can be poorly sampled



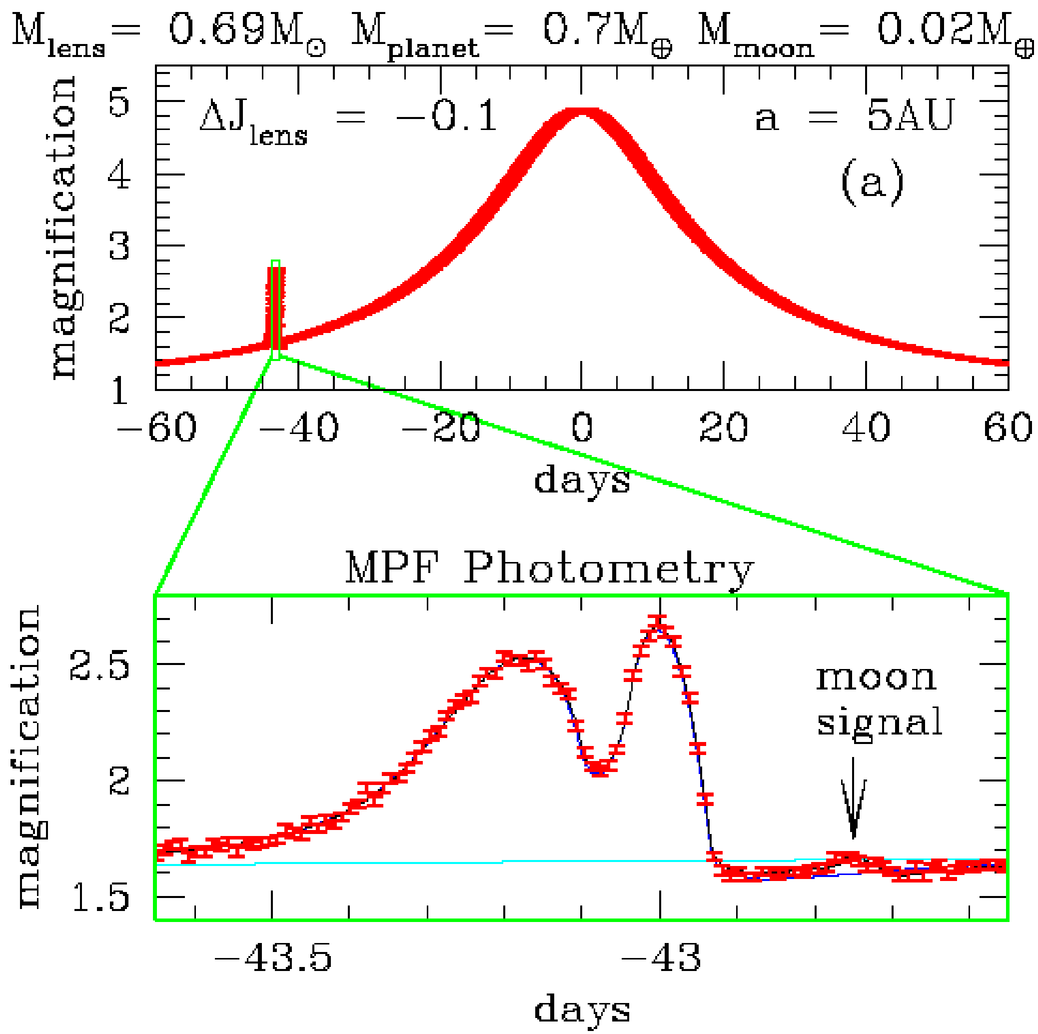
What can we expect from Space?

Example: Microlensing Planet Finder (Bennett PI)

- Simulations from Bennett & Rhie (2002)
- Basic results confirmed by independent simulations
- Continuous observations of 4×0.66 sq. deg. central Galactic bulge fields: $\sim 2 \times 10^8$ stars
- Observations in near IR to increase sensitivity
- ~15,000 events in 4 seasons

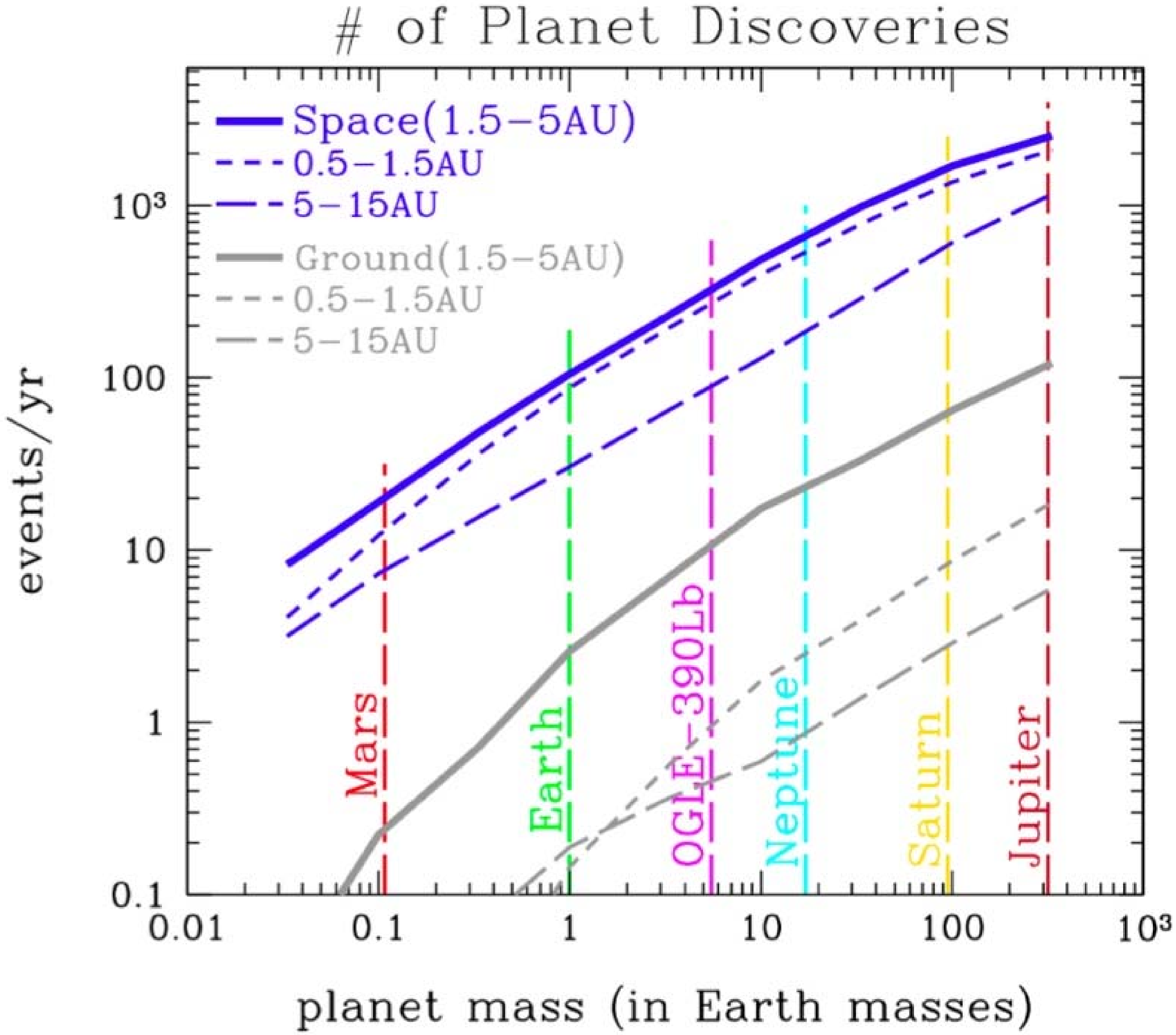
Simulated Planetary Light Curves

- Exposures every 10-15 minutes
- Strong signals
- Unambiguous information
- Moons detectable! (1.6 lunar masses)

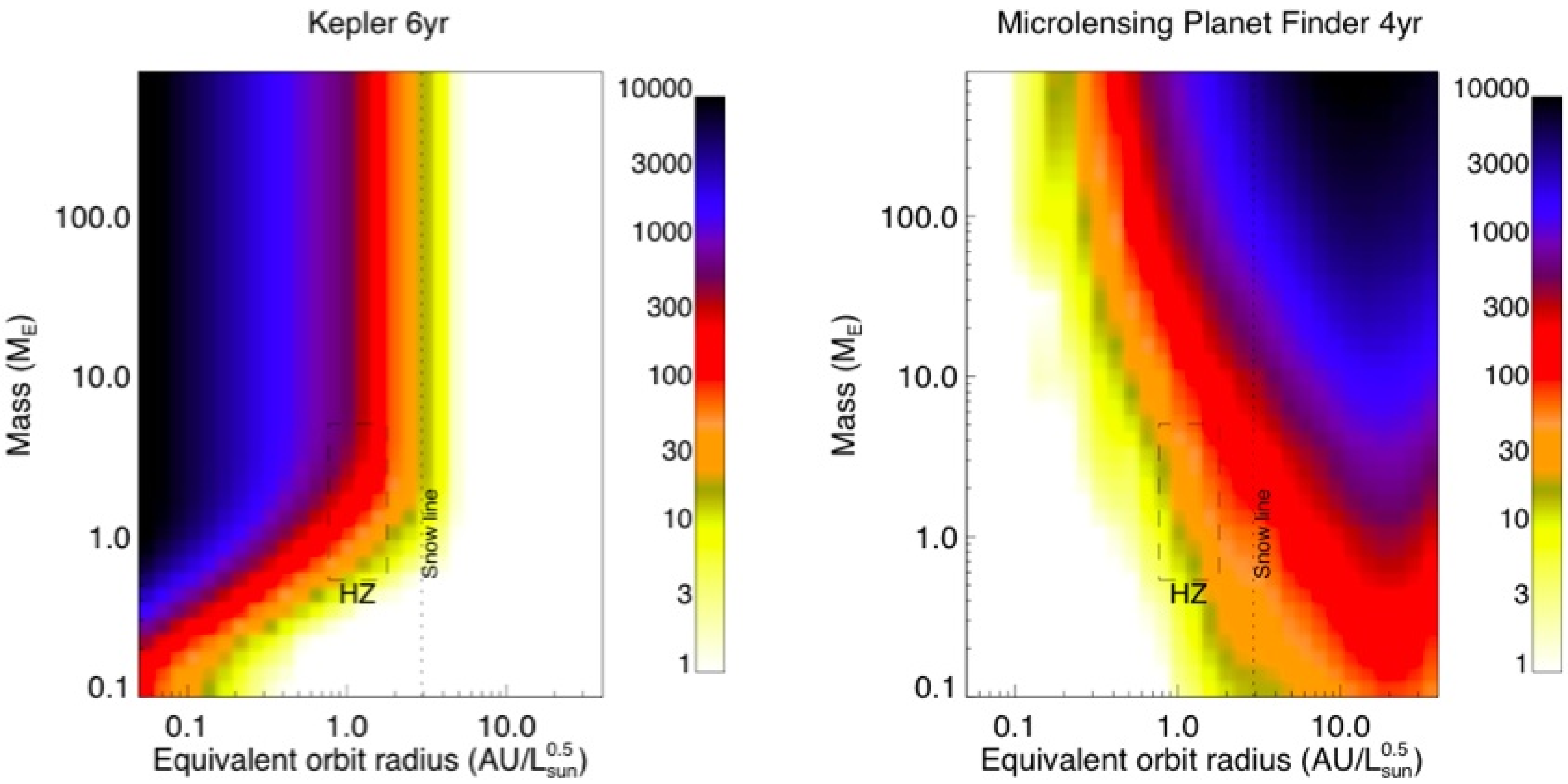


Bennett & Rhie (2002)

Wide Range of Separations

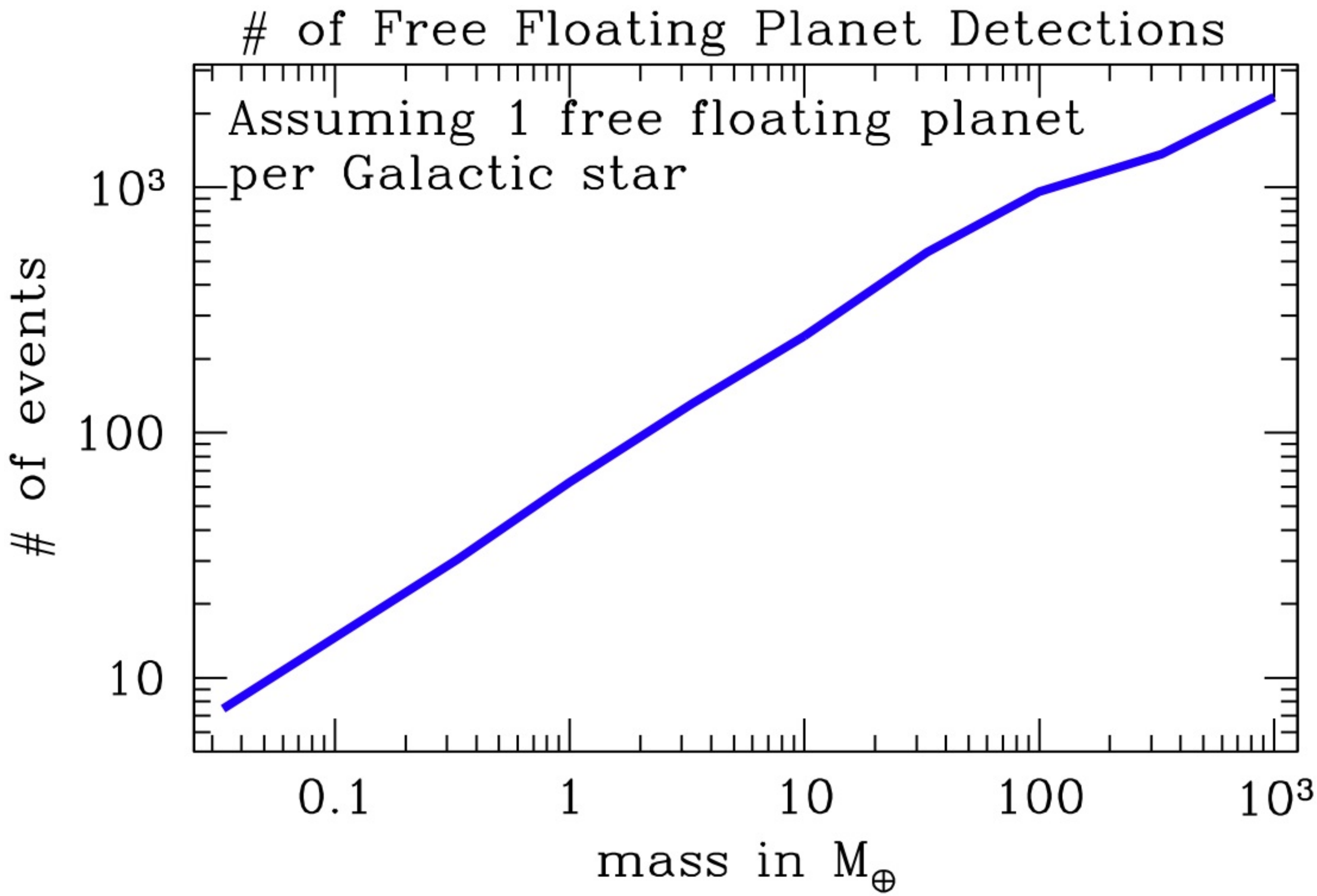


Habitable Planets



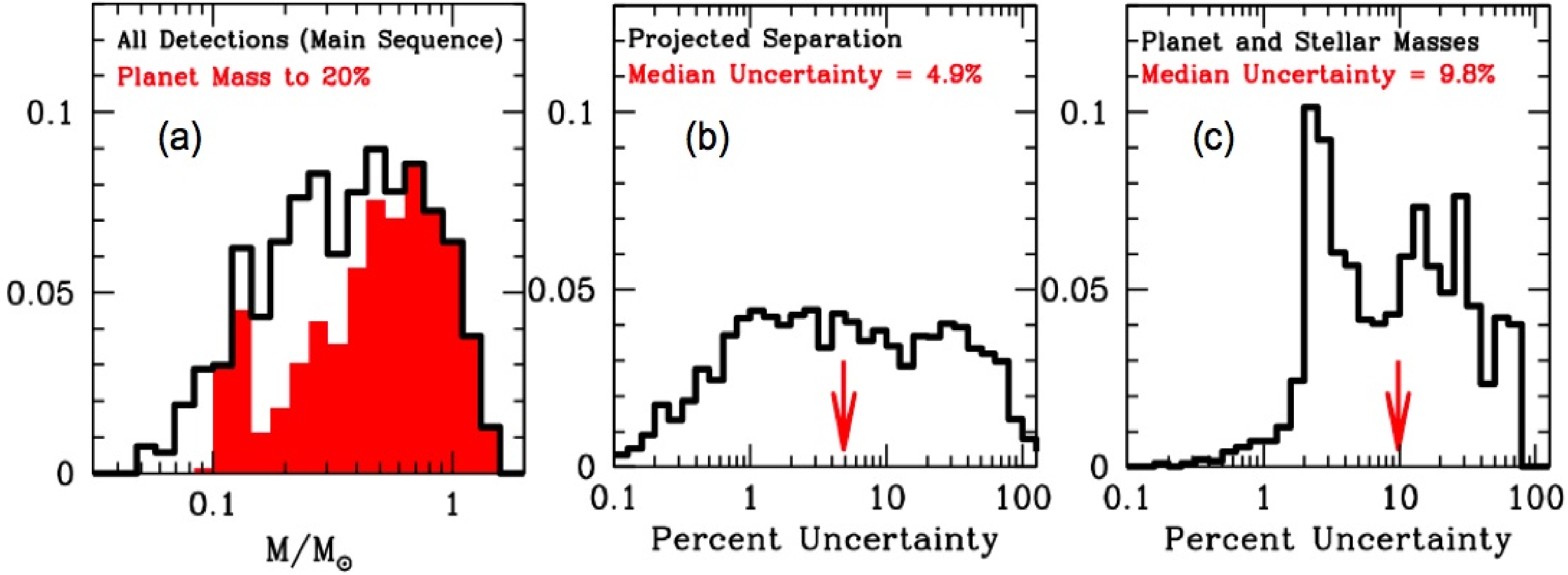
•Dozens of Earth-mass habitable planets
•Complements Kepler.

Free Floating Planets



Planet formation theories generically predict many free-floating planets.

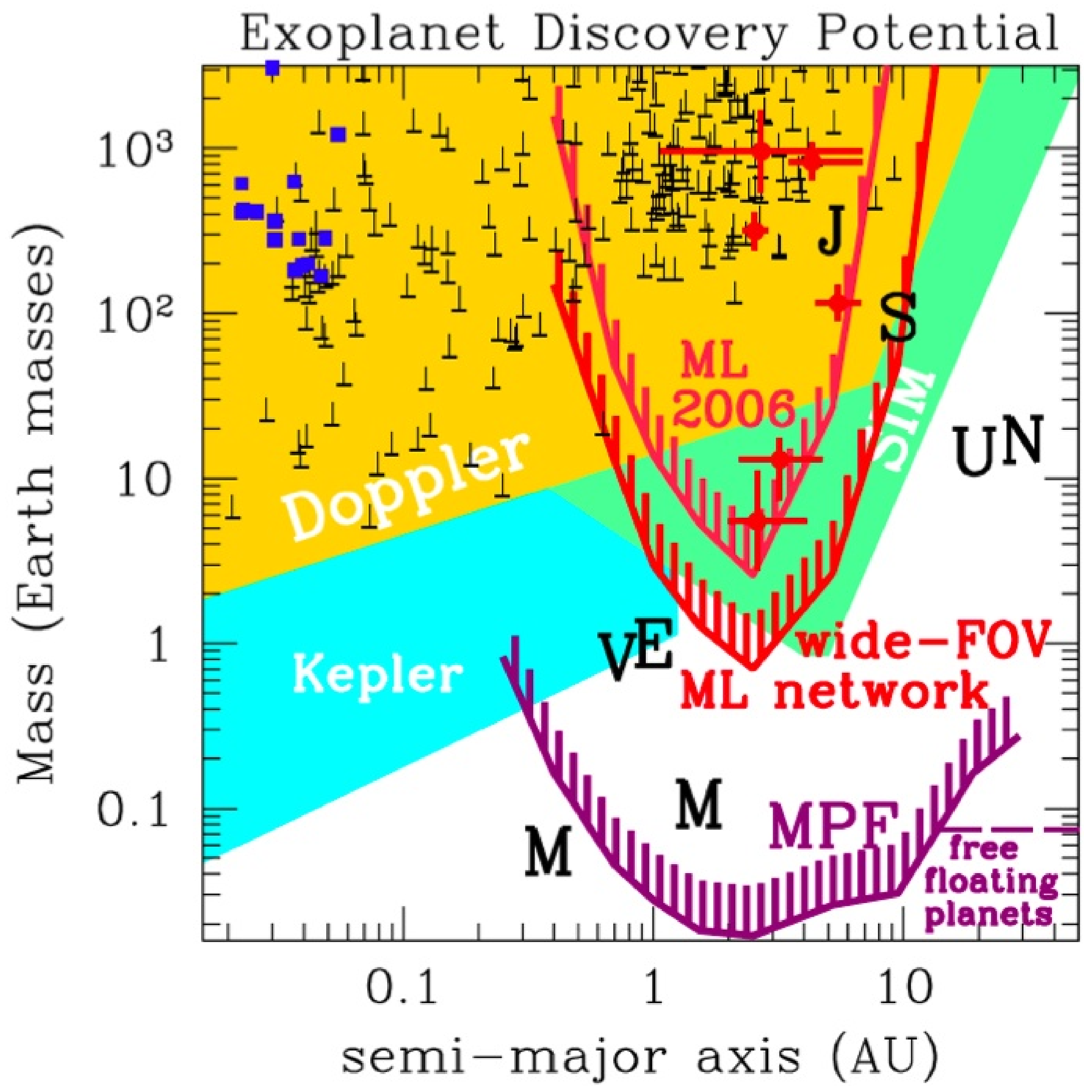
Lens Detection Provides Accurate Mass Estimate



- Lens will be detected for the majority of main-sequence lenses.
- Host star masses will be measured to 10% for half of the events.
- Projected separations will be measured to 5% for half of the events.

Planet Detection Sensitivity

- Sensitivity to all Solar System planet analogs except Mercury.
- Demographics of planetary systems - tests planet formation theories.
- Most sensitive technique for a ≥ 0.5 AU.
- Good sensitivity to "outer" habitable zone (Mars-like orbits) where detection by imaging is easiest.
- Complementary to Kepler.
- Assumes ≥ 9σ detection threshold.
- Can find moons and free floating planets.



Updated from Bennett & Rhie (2002) ApJ 574, 985

"Recommendation B. II. 2 Without impacting the launch schedule of the astrometric mission cited above, launch a Discovery-class space-based microlensing mission to determine the statistics of planetary mass and the separation of planets from their host stars as a function of stellar type and location in the galaxy, and to derive* $\eta_\oplus$ *over a very large sample.*

* *"Recommendation B. I. a. 1 Launch and operate a space based astrometric mission capable of detecting planets down to the mass of the Earth around 60-100 nearby stars…"*

Technology

- Ground-based 1-2m, Wide FOV Telescope
  - Several very similar telescopes already operating
    - MOA-II
    - Pan-STARRS-1 - $20M
- Space-based microlensing mission
  - Requires almost no technology development.
  - Can extensively leverage other missions (Spitzer, NextView, Ikonos, JWST)
  - Can use many components that are demonstrated on orbit or flight qualified.

MPF Misson Design

- 1.1-m aperture consisting of a three-mirror anastigmat telescope feeding a 147 Mpixel HgCdTe focal plane (35 2048^2 arrays)
- The spacecraft bus is a near-identical copy of that used for *Spitzer*.
- The telescope system very similar to NextView commercial Earth-observing telescope designs.
- Detectors developed for JWST meet MPFs requirements.
- All elements are at TRL 6 or better.
- Total Cost $300 (without launch vehicle)

Property	Value	Units
Launch Vehicle	7920-9.5	Delta II
Orbit	Inclined GEO 28.7	degrees
Mission Lifetime	4.0	years
Telescope Aperture	1.1	meters (diam.)
Field of View	0.95x0.68	degrees
Spatial Resolution	0.240	arcsec/pixel
Pointing Stability	0.048	arcsec
Focal Plane Format	145	Megapixels
Spectral Range	600-1700	nm in 3 bands
Quantum Efficiency	>75% >55%	900-1400 nm 700-1600 nm
Dark Current	<1	e-/pixel/sec
Readout Noise	<30	e-/read
Photometric Accuracy	1% or better	at J=20.5
Data Rate	50.1	Mbits/sec

MPF Mission Requirements

Dark Energy Synergy

- Space-based microlensing mission telescope requirements are very similar to the requirements for many proposed dark energy missions.
- Combined dark energy/planet finding mission probably could be accomplished at a substantial savings.
- ADEPT, Destiny, SNAP, DUNE/SPACE/Euclid
  - Wide FOV, >1.1m aperture, technical specifications appear to satisfy space-based microlensing survey specifications
  - DUNE/SPACE/Euclid can meet all the science goals without modification to hardware.
- Trade study:
  - Observing time
  - Pass bands
  - FOV and Detectors
  - Orbit
  - Telemetry
  - Aperture
  - Optics
  - Pointing

Summary

- Ground-based Next-Generation Survey: +$10M—$20M
  - Complete network with a single wide FOV 1-2m telescope in SA.
  - Frequency of planets $>M_\oplus$ beyond the snow line.
  - Test planet formation theories.
- **Either:** Space-based Microlensing Mission: +$300M + launch
  - Complete census of planets with mass greater than Mars and $a > 0.5$ AU.
  - Sensitivity to all Solar System planet analogs except Mercury.
  - Demographics of planetary systems - tests planet formation theories.
  - Detect “outer” habitable zone (Mars-like orbits) where detection by imaging is easiest.
  - Can find moons and free floating planets.
- **Or:** Joint μlensing/Dark Energy Mission +$100M—$200M?
- Total cost to “Exoplanet Community”: **$120M—$420M**